

DUST ENSHROUDED AGB VARIABLES IN THE LMC

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ABSTRACT. The luminosities and periods of obscured AGB stars in the LMC are discussed using a combination of ISO and ground-based infrared photometry. The bolometric luminosities of these stars fall close to an extrapolation of the period-luminosity relation derived for oxygen-rich Mira variables, with both oxygen- and carbon-rich stars falling close to the same relation. It has been known for many years that there are, in the Magellanic Clouds, significant numbers of large amplitude variables which have considerably higher luminosities than the period-luminosity relation would predict. Many of these can be shown to be undergoing hot bottom burning. It is speculated that all large amplitude AGB stars with luminosities significantly higher than indicated by the period-luminosity relation are undergoing hot bottom burning.

1. Introduction

The asymptotic giant branch (AGB) stars discussed here include those referred to as Mira variables, OH/IR stars and dusty carbon stars. The classical defining characteristics of Mira variables are: large amplitudes, emission line spectra, and periods in excess of about 100 days. The OH/IR and dusty carbon stars are assumed to be similar to the Miras although they are often too faint optically to determine visual amplitudes or measure spectra. Their periods are generally long, up to 1000 days for the carbon stars and up to about 2000 days for the OH/IR stars. A brief review is given below of red variables in globular clusters, prior to a more detailed description of obscured AGB variables in the LMC.

2. AGB Variables in Globular Clusters

Globular clusters provide a well studied and well defined environment in which to consider AGB variables. Oxygen-rich Miras are found only in metal-rich clusters where they are the most luminous stars in the clusters. The cluster semi-regular (SR) variables are less luminous than the Miras, but brighter than the non-variable stars. The luminosities of the Miras are greater than that of core helium flash, clearly putting them on the AGB. Broadly speaking stars evolve up the AGB to higher luminosity. But as is now well known, and as discussed elsewhere in these proceedings an AGB star's surface luminosity changes quite significantly during the course of the He-shell flash cycle. It seems likely therefore that stars enter and exit the Mira phase, possibly more than once,

as their luminosity changes during the course of the shell-flash cycle. There are rather few cluster Miras, as would be expected of an evolutionary phase that lasts no more than 2×10^5 years (Renzini & Greggio 1990).

In a period-luminosity (PL) diagram we find the low amplitude SR variables at shorter periods than the Miras. They are on an evolutionary track that leads to, and terminates at, the Mira PL relation (Whitelock 1986; Feast 1988). Thus we can understand the Mira period luminosity relation as the locus of the end-points of the evolution of stars with different mass and/or metallicity. Bedding & Zijlstra (1998) have recently suggested that the luminosities of local SR variables (which are presumably younger than the globular cluster SRs), as determined from Hipparcos parallaxes, follow an evolutionary track parallel to that found for globular cluster SR variables, but about 0.8 mag brighter. The SR variables near LMC clusters, studied by Wood & Sebo (1996), appear to follow roughly the same track as the local SRs. At this stage we have little observational evidence for what happens to stars of even higher initial mass which will evolve at higher luminosity. If, as mounting evidence suggests, the more massive stars are affected by hot bottom burning (HBB) it is quite possible that tracks for AGB stars of several solar masses are quite different.

When the AGB variables drop out of the Mira instability strip, during the low luminosity part of the flash cycle, they will become SR variables for some period of time. This type of SR may show a detached dust shell, from the previous high mass-loss Mira phase, and/or abundance anomalies, such as technetium from the dredge-up which accompanies certain thermal pulses. However, by analogy with the globular clusters¹ the majority of oxygen-rich SRs must be in a pre-Mira evolutionary phase and are not expected to show abundance anomalies.

3. AGB stars in the Large Magellanic Cloud

In the following discussion we adopt a distance modulus for the LMC of 18.5 mag, as used in most of the papers to which references are made. The best current distance estimates put it slightly further away (e.g. Feast 1999) so the luminosities discussed here are conservative ones. Our knowledge of AGB variables in the LMC up to a few years ago is nicely illustrated in the PL diagram, Fig. 1, taken from Wood et al. (1992) which was originally produced to show the position of the then newly discovered OH/IR stars. The high luminosity stars were thought to be supergiants, with initial masses in excess of about $8 M_{\odot}$. The fainter stars are on the AGB, and superimposed are model tracks suggesting their approximate initial masses. The stellar luminosities were derived from single observations of large amplitude variables, so a good deal of the scatter is due to variability. As discussed above, we have good reason to believe that, certainly at low masses, stars only become Miras for a short while, so that only part of any evolutionary track is populated by Miras. The picture has changed somewhat in very recent times with the discovery and detailed investigation of more AGB variables with thick shells, as discussed below.

¹ In cluster HR diagrams SRs occupy the luminosity range between non-variables and Miras; unless this represents an evolutionary sequence there will be an unexplained luminosity gap between the non-variables and the Miras.

Fig. 1. LMC red variables from Wood et al. (1992 - fig 8); squares are supergiants (but see section 4) and circles are AGB stars. Solid symbols are OH Masers. Fig not included in astro-ph.

Feast et al. (1989) established PL relations for carbon- and oxygen-rich Miras in the LMC. These were derived from large amplitude variables monitored over their light cycles to derive mean luminosities. At K the carbon and oxygen stars obey the same PL relation with a scatter of only 0.13 mag, up to periods of around 420 days. Bolometric luminosities were determined by fitting blackbodies to JHK photometry - a reasonable approximation for these stars which have only very thin dust shells. The bolometric PL relations appeared to be different for the oxygen- and carbon-rich Miras, although it was never clear if this was really so, or if it was an artifact of the way the bolometric luminosities were derived. Groenewegen & Whitelock (1996) derived a bolometric PL relation for LMC carbon Miras using all the available data for spectroscopically confirmed C stars, although there were only single epoch observations for many of these. Their PL relation was essentially indistinguishable from that for the O-rich stars. At the time this work was done no LMC carbon Miras were known with periods significantly longer than 500 days, and the optically visible oxygen-rich stars with periods over 420 days lay clearly above the PL relationship. One of these luminous AGB stars, RCG 69 (0523-6644), was among the sample looked at by Smith et al. (1995) for lithium, and is in fact lithium-rich.

Smith et al. (1995) made a survey for lithium among AGB stars in the SMC and LMC, and found that a very large fraction of those with $-6 > M_{bol} > -7$ were lithium rich, as were a much smaller number of lower luminosity stars. Our present understanding of lithium enhancements in AGB stars (e.g. Sackmann & Boothroyd 1992) is that they occur principally as a result of HBB. Towards the end of AGB evolution, for stars with an initial mass in the range 4 to 6 M_{\odot} , the base of the convective envelope can dip into the H-burning shell, with far reaching consequences for the evolution of the star.

The transition from O- to C-rich is affected; exactly how seems to depend on the model and in particular on how mass loss is treated. HBB may prevent carbon stars forming at all, or prevent them from happening until the envelope mass is depleted (Frost et al. 1998). In some models C stars do form and then HBB turns them back into O-rich stars (Marigo et al. 1999). Another consequence, for stars in a rather narrow mass range, is the formation of lithium via beryllium. One of the most important results in the present context is a rapid increase in luminosity (Blöcker & Schönberner 1991); again the details depend on mass loss which tends to decrease the effect of HBB. In view of this it is interesting to note that most of the stars illustrated in fig. 6 of Smith et al. (1995) lie above the PL relation and many of these must be undergoing HBB, as their lithium abundance indicates. As it is possible for some stars to experience HBB without showing lithium enhancements (e.g. Mazzitelli et al. 1999) we speculate that all of the stars with luminosities above the PL are there because of HBB. Note that the group of stars discussed by Smith et al. is not representative of AGB stars generally. These are the stars for which it is practical to get optical spectra with sufficient resolution and signal-to-noise to measure lithium line strengths, i.e. the brightest ones with the thinnest dust shells. Furthermore, the luminosities of these stars require more detailed investigation; most are based on single observations of large amplitude variables. The periods are not all well defined and it is possible that some of the stars are SR variables and should not properly be included in this discussion.

Wood (1998) discussed the results of a long term investigation of nine obscured IRAS sources in the LMC, providing periods ($530 < P < 1295$ days) and luminosities for them. Six of these sources are significantly fainter than an extrapolation of the PL relation and he speculated that these were C stars - available evidence on the subject being somewhat contradictory. IR spectroscopy, either from the ground or from ISO (*ISOPHOT* or *ISOCAM*), demonstrates that all but one of Wood's nine sources are indeed C stars, the presence of the $3\mu\text{m}$ $\text{C}_2\text{H}_2 + \text{HCN}$ feature being a clear diagnostic of carbon-rich chemistry (van Loon et al. 1999b or references therein). The one exception was the star with the longest period which Wood et al. (1992) had already shown to be an OH source, and therefore O rich. Wood's (1998) conclusion, from the discovery of apparently subluminoous C stars, was that his observations “... *clearly demonstrate that once significant mass loss and dust formation occurs, large amplitude LPVs no longer fall on the tight $M_{\text{bol}}/\log P$ relation found for Mira variables with $P < 450$ days*”.

The nine stars discussed by Wood are also a subgroup of about 50 LMC sources, originally selected from IRAS data, for which a group of us have been obtaining ground-based and ISO data over the last few years (van Loon et al. 1999b and references therein). We have derived periods for them, which can be further refined by combining our data with Wood's; these do not differ significantly from those measured by Wood. Van Loon et al. (1999b) combined *ISOCAM* and/or *ISOPHOT* photometry and spectroscopy with ground based, *JHKL*, photometry and fitted models to derive an independent luminosity for these (and other) stars. These results illustrate the luminosity *at the time of the ISO observations*, i.e. at random phase, whereas Wood (1998) combined IRAS observations, after applying a correction intended to reproduce mean light, with mean near-infrared photometry. A comparison of our estimates of the C-star luminosities with those from Wood is shown in Fig. 2. Three of the stars agree, while we find brighter

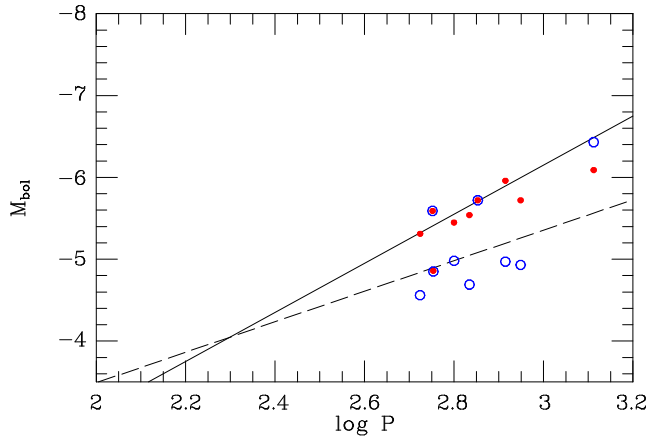


Fig. 2. A comparison of luminosities from Wood (1998) (open circles) and van Loon et al. (1999b) (closed circles) for the stars in common. The solid and broken lines are extrapolations of the PL relations for O- and C-rich stars, respectively, determined by Feast et al. (1989).

luminosities for the other five. The OH/IR star is slightly fainter than Wood found. Our observations were made at random phases, and a rough check suggests that two are close to mean light, two fainter and four brighter than mean light. The reason for the apparent systematic difference between the van Loon et al. and the Wood luminosities is not immediately obvious and requires more detailed investigation, but in view of Fig. 2 and the discussion below it seems premature to conclude that sources with thick dust shells fall systematically below the PL relation.

The analysis of our complete sample of LMC stars is at a preliminary stage so the details of the following discussion may change. Combining preliminary periods with luminosities derived by van Loon et al. (1999b), in the same way as those discussed for the Wood (1998) sources, we obtain the PL data illustrated in Fig. 3. Several of the long period O-rich stars are also OH sources (Wood et al. 1992). Extrapolations of the Feast et al. (1989) PL relations are shown; note that the PL relation determined by Groenewegen & Whitelock (1996) for C stars extrapolates between the two lines

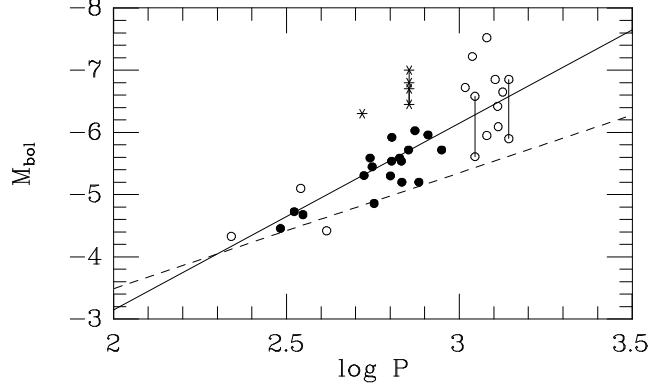


Fig. 3. The PL relation for long period AGB stars in the LMC. The luminosities are from van Loon et al. (1999b) and are single phase measurements. The periods are from Whitelock et al. (in preparation). The solid and broken lines are extrapolations of the PL relations, determined by Feast et al. (1989), for O- and C-rich stars, respectively. Solid symbols represent C stars and open ones O-rich stars. The stars marked as asterisks are IRAS04496-6958 and SHV F4488 which are both C-rich (but see text). Connected points represent measurements of the same star at different epochs.

illustrated. In interpreting Fig. 3 it is crucial to remember that the luminosities shown here are one-off measurements of large amplitude variables, because we have, in general, only single epoch ISO observations. It is therefore obvious that a good deal of the scatter in this diagram is due to variability and multiple observations of three stars give some impression of this. It is also clear that these data scatter around the extrapolated O-rich PL relation, with both C- and O-rich stars falling close to the same line.

The best sampled light curves for the LMC carbon stars have data spanning 5 to 6 years and show peak-to-peak amplitudes of $\Delta K \sim 2$ mag. Several of the C stars exhibit apparently secular variations on top of the regular pulsations, as do many galactic C-stars with high mass-loss rates (Whitelock et al. 1997), probably the results of fluc-

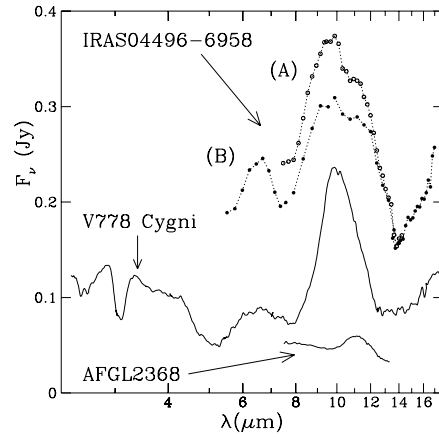


Fig. 4. *ISOCAM* spectrum of IRAS04496–6958 exhibiting both silicate and SiC emission features. Shown for comparison are V778 Cyg, a C star with a silicate shell, and AFGL 2368, a thick shelled C star. Figure from Trams et al. (1999)

tuations in the mass-loss rate. It is difficult to establish the bolometric amplitudes of these stars as few have been monitored at wavelengths longer than $3\mu\text{m}$ where most of the energy is emitted. Nevertheless, the discussion by van Loon et al. (1998) suggests that the C stars may have $\Delta m_{bol} \sim 1.0$, while the O-rich stars with $P > 1000$ days will have $1.0 < \Delta m_{bol} < 1.5$ mag.

4. HBB in Individual Stars

The four separate estimates of the luminosity of IRAS04496–6958 are shown as connected asterisks in Fig. 3 (van Loon et al. 1998, 1999a, 1999b). The $3\mu\text{m}$ spectrum of this star shows a clear $C_2H_2 + HCN$ absorption feature, indicating it is a C star. Its $10\mu\text{m}$ spectrum (Fig. 4), however, is very unusual in that it shows both silicate and silicon carbide features, suggesting a mixed O- and C-rich chemistry (Trams et al. 1999). This is the first example of an extragalactic carbon star with silicate emission. There are several galactic stars which show similar combination features; they are generally understood to be binary systems in which one component is a carbon star and the silicate dust resides in a circum-binary disk (Lloyd Evans 1990). It may be that the same explanation applies here, although in view of its high luminosity, Trams et al. (1999) offered an alternative explanation – that IRAS 04496–6958 was, until recently, a star undergoing HBB, hence the silicate dust. It would thus be an example of a star in which HBB terminated, perhaps due to mass-loss, and which then underwent a thermal pulse and dredge-up turning it into a C star.

The solitary asterisk in Fig. 3 represents a C star which Smith et al. (1995) found

to be lithium rich, SHV F4488. The luminosity used here, $M_{bol} = -6.3$, is considerably brighter than that quoted by Smith et al., $M_{bol} = -5.7$, which was taken from Hughes & Wood (1990). The difference could be due to variability or possibly Hughes & Wood, who had *JHK* photometry from only one epoch, underestimated the flux. In any case the enhanced lithium tells us that the star is undergoing HBB.

IRAS 04496–6958 and SHV F4488 are more luminous than the other C stars shown in Fig. 3. They lie in the same region of the PL diagram, above the extrapolation of the Mira relation, as do the luminous O-rich AGB stars discussed by Feast et al. (1989) and as do almost all of the lithium-rich stars discussed by Smith et al. (1995).

Finally, it should be noted that one of the stars marked as a short period supergiant in Fig. 1, HV 2572, is among the Smith et al. (1995) lithium-rich sample and must therefore be an AGB star undergoing HBB, not a supergiant.

5. Conclusions

Observations of large amplitude variables in the LMC show the following:

1. those which are close to the end of their AGB lifetimes fall close to the Mira PL relation;
2. C- and O-rich Miras obey the same PL as well as we can currently establish;
3. many, perhaps all, of the AGB variables which lie above the PL relation are undergoing HBB.

There is a caveat on item 2 above: we cannot as yet eliminate the possibility that there are stars which lie below the PL, as limitations in the sensitivity of our surveys may have prevented us from detecting them as yet. In this regard we should look at the Galactic Centre where there is evidence for long-period large-amplitude variables with low luminosities (Blommaert et al. 1998; Wood et al. 1998). Finally, if we really want to know the luminosities of these large-amplitude variables we need to monitor them at longer wavelengths than has been done to date.

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